# Extensive air showers with TeV-scale quantum gravity

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One of the possible consequences of the existence of extra degrees of freedom beyond the electroweak scale is the increase of neutrino-nucleon cross sections ($\sigma_{\nu N}$) beyond Standard Model predictions. At ultra-high energies this may allow the existence of neutrino-initiated extensive air showers. In this paper, we examine the most relevant observables of such showers. Our analysis indicates that the future Pierre Auger Observatory could be potentially powerful in probing models with large compact dimensions.

Recently, it has become evident that a promising route to reconcile high energy particle physics and gravity is to modify the nature of gravitational interactions at distances shorter than a millimeter. Such a modification can be most simply achieved by introducing extra dimensions in the sub-millimeter range [1]. In this approach the fundamental scale of gravity $M_*$ can be lowered all the way to $\mathcal{O}$ (TeV), and the observed Planck scale turns out to be just an effective scale valid for energies below the mass of Kaluza–Klein (KK) excitations. Clearly, while the gravitational force has not been directly measured beneath the millimeter range, Standard Model (SM) interactions have been fairly well investigated below this scale; so if large extra dimensions really exist, one needs some mechanism to prevent SM particles from feeling those extra dimensions. Remarkably, there are several possibilities to confine SM fields (and even gravity) to a 4 dimensional subspace (referred to as a 3-brane) within the $(4 + n)$ dimensional spacetime [2]. The provocative new features of this scenario have sparked a flurry of activity to assess its experimental validity. A brief resumé of current theoretical work devoted to higher dimensional models includes topics addressing fundamental issues of phenomenology [3], cosmology [4], astrophysics [5], and gravity [6]. Moreover, an intense effort to find signatures of extra-dimensions in collider data is currently underway [7].

Since 1966, a handful of extensive air showers have been observed corresponding to what seem to be single particles carrying over $10^{20}$ eV [8]. This, in itself, is remarkable, as it is difficult or even impossible to explain how such energies can be attained by conventional acceleration mechanisms [9]. Deepening the mystery, it was pointed out by Greisen, Zatsepin and Kuz'min [10] (GZK) that extremely high energy ($\gtrsim 10^{20}$ eV) cosmic rays, if nucleons and/or nuclei, would lose energy rapidly through interactions with the cosmic microwave background (CMB). This leads to the so-called GZK cutoff, which limits the propagation distance of these particles to roughly 50 Mpc. The difficulty in constructing nearby astrophysical sources that could accelerate particles to such high energies led to the belief that beyond roughly $10^{20}$ eV, no cosmic rays would be detected. Adding to the puzzle, the arrival directions of these events are distributed widely over the sky, with no plausible optical counterparts (such as sources in the Galactic plane or in the Local Supercluster). Furthermore, the "super-GZK" data are consistent with an isotropic distribution of sources in sharp contrast to the anisotropic distribution of light within 50 Mpc from Earth [11]. In conclusion, the current picture is very unclear. It is worthwhile to consider whether new physics could be at play.

Of particular interest here, the extraordinarily high center-of-mass (c.m.) energies achieved at the top of the atmosphere are well above those necessary to excite the hypothetical KK modes which would reflect a change in spacetime dimensionality [12]. Hence, a detailed analysis of extensive cosmic ray showers, taking into account this departure from previous fundamental particle theory, is worthwhile [13].

Interestingly enough, if gravity becomes strong at energies of a few TeV, virtual graviton exchange can produce relatively large effects on the high energy scattering cross section, drastically changing the neutrino-nucleon interaction [14]. Neutrinos can propagate through the CMB essentially uninhibited, breaking the GZK barrier [15]. Unfortunately, within the SM scenario a neutrino incident vertically on the atmosphere would pass through it unihibited as well, never initiating an extensive air shower. It was already noted that within the extra dimensional framework, the neutrino nucleon cross section can approach typical hadronic values at c.m. energies $s \gtrsim 400$ TeV, allowing earlier development of a vertical neutrino induced shower [16–18]. One may wonder whether the growth of the cross section carries with it observable deviations from SM predictions. Consistency with current experimental data requires [19],

$$\sigma(E) \lesssim 3 \times 10^{-24} \, \frac{E}{10^{19}\,\mathrm{eV}} \, \mathrm{cm}^2. \qquad (1)$$

This bound certainly does not challenge the neutrinos acquiring a hadronic-scale cross section.

A complete theory of massive KK modes has yet to see the light of day, making it impossible to know the exact cross section at asymptotic energies. Any air shower analysis would thus depend on reliable guesswork, supplemented with generally accepted theoretical principles like duality, unitarity, Regge behavior and parton structure. Roughly speaking, Reggeized spin 2 graviton exchange predicts a $s^2$ dependence of the cross section [14].

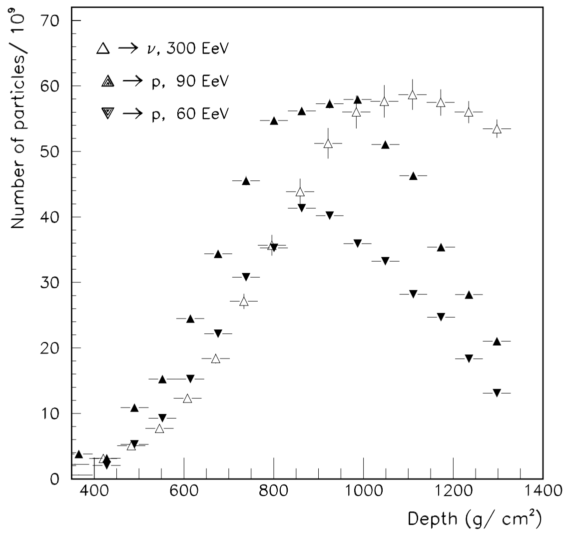


FIG. 1. Longitudinal development of neutrino and proton showers for different primary energies and primary zenith angle 43.9○. The error bars indicate the standard fluctuations of the means.

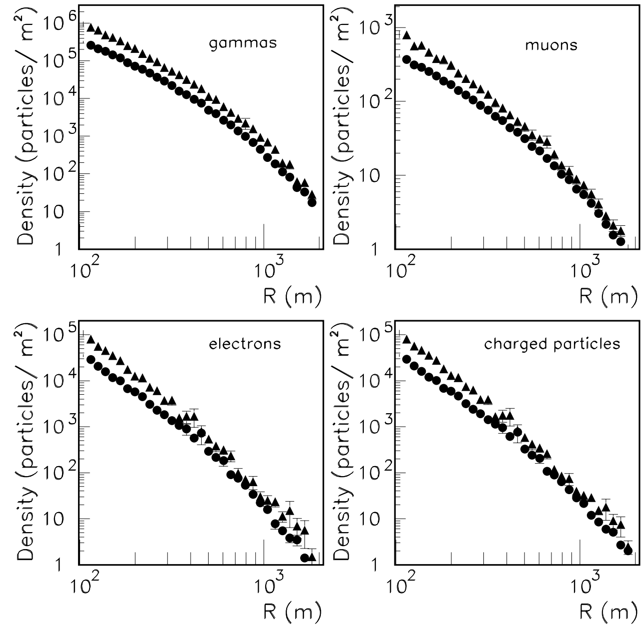


FIG. 2. Lateral distributions of vertical 300 EeV neutrino induced showers (triangles), and 60 EeV proton-induced showers (circles). The error bars indicate the RMS fluctuations.

More conservative arguments that entail (by construction) a unitarized amplitude and cross section, suggest a linear growth in $s$ ($\sigma \propto s^2$ does not automatically do this).* Hereafter, we refer the discussion to the case of 2-flat extra dimensions where the total neutrino nucleon cross section can be well approximated by [20]

$$\sigma_{\nu N} \approx \frac{4\pi s}{M_*^4} \approx 10^{-28} \left(\frac{M_*}{\mathrm{TeV}}\right)^{-4} \left(\frac{E}{10^{19}\,\mathrm{eV}}\right) \mathrm{cm}^2. \quad (2)$$

To simulate the consequences of this for $\nu$-induced air showers, we assume that the increase in the cross section is driven by the production of minijets [21]. Furthermore, we adopt the SIBYLL package to model the fragmentation region at ultra high energies [22]. The reader should keep in mind the crudeness of this approximation. However, as we discuss below most of the expected qualitative features in the shower can be quite well reproduced. The algorithms of AIRES (version 2.1.1) [23] are slightly modified so as to track the particles in the atmosphere. In particular, Eq. (2) is translated into the neutrino mean free path

$$\lambda_\nu = \frac{m_{\mathrm{air}}}{\sigma_{\nu\mathrm{air}}}, \quad (3)$$

via the standard 8 parameter function used in AIRES,

$$\lambda_\nu = P_1 \, \frac{1 + P_2\ u + P_3\ u^2 + P_4\ u^3}{1 + P_5\ u + P_6\ u^2 + P_7\ u^3 + P_8\ u^4}\ \mathrm{g\,cm}^{-2}. \quad (4)$$

Here $m_{\mathrm{air}}$ [g] is the mass of an average atom of air, and $u = \ln E$ [GeV]. The coefficients $P_i$ are listed in Table I for different values $M_*$.

Several sets of neutrinos were injected at 100 km above sea level. The sample was distributed in the energy range of $10^{20}$ eV up to $10^{21}$ eV, and was uniformly spread in the interval of 0° to 60° zenith angle at the top of the atmosphere. All shower particles with energies above the following thresholds were tracked: 750 keV for gammas, 900 keV for electrons and positrons, 10 MeV for muons, 60 MeV for mesons and 120 MeV for nucleons. The results of these simulations were processed with the help of the AIRES analysis package.

Figure 1 shows the total number of charged particles versus atmospheric depth averaged over 25 showers for the case of a 300 EeV neutrino at $M_*$=1 TeV. For comparison, proton-induced showers at 60 and 90 EeV are shown on the same figure. As showers initiated by neutrinos typically start later than proton-induced showers, the longitudinal development tends to level off after reaching a maximum, in contrast to a standard air shower which decreases more rapidly after reaching a maximum. The number of charged particles produced in the cascade de-

*Notice that if one requires the neutrino-nucleon cross section to satisfy the Froissart bound, it will remain under about 1 mb and the atmosphere will be transparent to neutrinos [17].

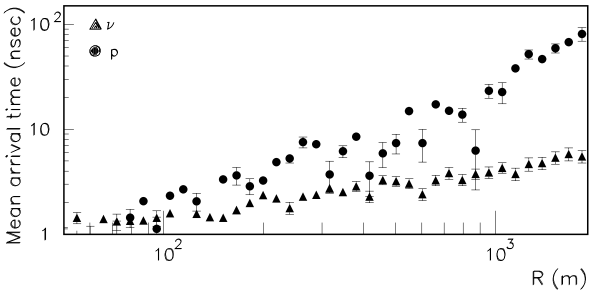


FIG. 3. Arrival times for charged particles in vertical 300 EeV neutrino and 60 EeV proton showers normalized at 50 m from the shower core. The error bars indicate the RMS fluctuations.

pends on the amount of energy deposited in the atmosphere by the primary. Neutrinos at the energy and mass scale shown in the figure typically suffer 2 interactions in the atmosphere; any energy remaining after this is undetected. By comparing the neutrino-induced showers to the proton-induced showers shown in the figure, one can roughly estimate the inelasticity to be $0.1 < y < 0.15$. This is consistent with the estimates of reference [24].[†]

Figure 2 shows the lateral distributions for showers produced by 300 EeV neutrinos and 60 EeV protons. At 50 m from the core, the ratio of the number of charged particles in the neutrino shower to that in the proton shower is $\approx 3.5$. However, at about 1 km from the core the ratio reduces to $\approx 1.5$. This is significant since experiments which rely on surface detectors to determine shower parameters typically use samples taken on the order of 1 km from the core, and thus would not be able to easily distinguish between these two shower types.

Figure 3 shows the radial dependence of the mean arrival time of muons for showers initiated by 300 EeV neutrinos and 60 EeV protons. It can be readily seen from the comparison that the proton-induced showers exhibit larger fluctuations than the neutrino-induced showers. Besides, each profile presents a well defined slope that characterizes the shower front and comprises a signature of the primary spieces. In particular, a neutrino interacts in the atmosphere only once or twice, and consequently the muons reach the ground with a relatively short time delay.

The simulated neutrino showers discussed so far deposit far less energy in the atmosphere than the most energetic of the observed cosmic ray events. A natural question is then what the shower profile would look like for a neutrino whose energy and mean free path are

[†]It is important to stress that the maximum number of charged particles produced in a proton-induced shower does not depend on the hadronic interaction model [25], making the present estimate on the inelasticity quite reliable.

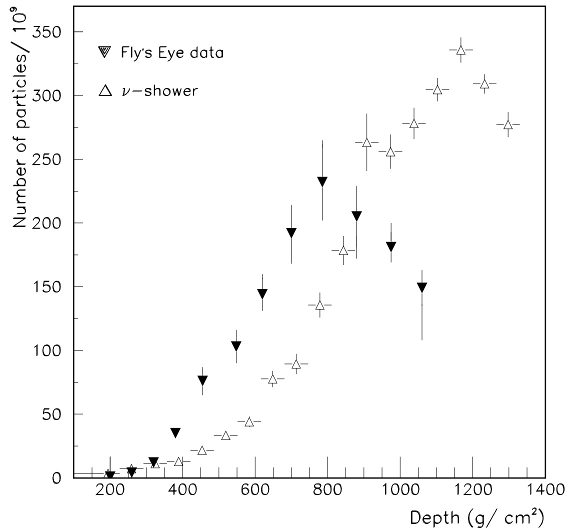


FIG. 4. The longitudinal development of a 900 EeV neutrino-induced shower is shown together with the experimental data reported by Fly's Eye. The error bars in the simulated points indicate the standard fluctuations of the means.

such that it would deposit roughly the same energy as observed in the highest energy event [26].

At this stage, it is important to point out that within the SM framework neutrinos are produced at extremely high energies, typically by the weak decay of pions or other hadrons. Thus, one needs protons to be accelerated to energies a few orders of magnitude even higher. In scenarios involving *precocious unification* [27], there may be alternatives to decay chains for producing super-GZK neutrinos at the source.

Figure 4 shows the longitudinal development of a 900 EeV neutrino-induced shower with a fundamental mass scale $M_* = 1.3$ TeV. We stress that such scale is above the upper bound for $M_*$ derived from the expected flux of neutrinos and current non-observation of horizontal air showers [20]. The total energy deposited in the atmosphere (after 2 interactions) is of the same order as the Fly's Eye event, but the shower maximum occurs, as expected, significantly later.

In summary, it has been proposed [16–18] that the GZK cutoff can be skirted if the progenitors of the most energetic air showers are neutrinos. Under this hypothesis, the neutrino-nucleon cross section is increased by the presence of extra dimensions, allowing the neutrinos to interact in the atmosphere. Simulations indicate that neutrino-induced showers at energies of a few hundred EeV would exhibit signatures distinct from those of proton (or nucleus) induced showers that deposit a similar amount of energy in the atmosphere. Similarly, if there are neutrinos energetic enough to deposit as much energy in the atmosphere as is observed in the highest energy events, it appears they too may have unique signatures. In fact, any physics beyond the standard model that increases the neutrino-nucleon cross section should affect shower observables like longitudinal profile (measured with fluorescence detectors) and ground particle distributions (measured with surface detectors). This article contains some qualitative discussion of relevant observables of neutrino-induced showers. As far as we are aware, no showers have been observed which are consistent with these features. If candidates are eventually discovered, of course it will be necessary to carry out a much more detailed simulation that the one presented here. We note that future hybrid detectors such as the Pierre Auger Observatory [28] will be in an exceptional position to search for such phenomena.

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TABLE I. Coefficients for mean free path parametrization

| $M_*$ [TeV] | $P_1$ | $P_2$ | $P_3$ | $P_4$ | $P_5$ | $P_6$ | $P_7$ | $P_8$ |
|---|---|---|---|---|---|---|---|---|
| 1 | -14657 | -2254.4 | -13.931 | 3.3530 | -1236.7 | -814.89 | -4.6945 | 1.7814 |
| 1.2 | 5654.4 | 1130000 | 1393 | -1417.3 | -1724000 | -124980 | 100.44 | 316.09 |
| 1.3 | 6638.5 | 307640 | 355.94 | -366.14 | -1499700 | -19822 | 845.46 | 91.015 |